MESO-SCALE OPTIMISATION OF 3D COMPOSITES AND NOVEL PREFORMING TECHNOLOGIES

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ABSTRACT

Various 3D woven composites have been studied and used in last several decades. It was demonstrated that these composites can have better delamination and impact resistance than conventional laminates. However, most of the 3D woven reinforcements have fibres only in two directions, warp and weft, because of weaving manufacturing constraints. This makes properties of 3D woven composites sub-optimal for most of the practical load cases. Relaxing manufacturing constraints and optimising 3D fibre architectures for more complex load cases requires new numerical meso-scale optimisation framework as well as novel manufacturing techniques to implement optimised fibre architectures.

This paper presents a numerical optimisation framework which employs TexGen modelling schema and links the meso-scale unit cell properties with the macro-scale response of a composite part. The framework is applied to a vehicle floor panel for demonstration purposes. It is shown that multi-axial 3D preforms can give up to 30% weight-saving compared to aluminium parts and outperform parts made from non-crimp fabric by about 10%. Initial development of manufacturing techniques for mutli-axial 3D preforms is presented as well.

1 INTRODUCTION

Composites with 3D fibre reinforcements usually provide better delamination and impact resistance when compared to conventional laminates. In addition, use of 3D fibre reinforcements can simplify the composites manufacturing process by removing the layup stage. However, the vast amount of possible reinforcement designs makes it difficult to select the most appropriate reinforcement for a particular application. Numerical modelling and optimisation can help to make this process faster and achieve greater performance. This paper presents a numerical optimisation framework which performs optimisation of meso-scale fibre architecture geometry.

A number of techniques have been developed to select the most appropriate laminate layup for many problems. These techniques, mostly based on optimisation algorithms, demonstrated potential weight savings from using optimised layups [1]. Similar optimisation was performed on some geometrical parameters of orthogonal 3D woven composites and resulted in up to 20% reduction of weight [2-4]. Optimisation of an orthogonal 3D weave resulted in up to 50% increase of buckling resistance as shown by Zeng et al. [4]. Yarn spacing, yarn thickness and other parameters were optimised to improve performance of a stiffened panel [2] and an automotive structure [2]. However, commercially available 3D woven textile composites do not have properties required for many applications because fibres are placed only in two orthogonal directions. New weaving techniques can create 3D weaves with off-axis yarns [5] but are still limited in terms of which fibre orientations, stacking pattern and binder path are achievable.

The framework, presented in this paper, relies on the mutli-scale approach, details of which are outlined in Section 2. The numerical implementation of the multi-scale approach and the optimisation procedure are demonstrated in Section 3 on a case study where an optimal reinforcement showed benefits over conventional laminates. The identified optimal reinforcements are not necessarily possible to manufacture with existing manufacturing techniques but these optimal solutions can be used to drive development of new techniques such as off-axis tow placement described in Section 4.

2 OPTIMISATION FRAMEWORK

The aim of the optimisation framework in this work is to optimise performance of a composite part on the macro-scale level by changing meso-scale geometry of the reinforcement. The multi-scale approach is the most suitable approach to address this problem. This makes it possible to analyse meso-scale and macro-scale problems separately providing appropriate procedures are followed. Results of the meso-scale analysis, elastic material properties, are used as input for the macro-scale problem, which requires these properties to simulate deformation of the composite part. Once the macro-scale problem is solved its results, e.g. local strains, can be used to restore a particular stress-strain state in the meso-scale reinforcement. Finally, the results of the macro-scale simulations, e.g. displacements, can be used in the optimisation procedure, which e.g. can aim to maximise the stiffness under the weight constraints. The meso-scale analysis is linked with the optimisation procedure by parametrisation of the meso-scale geometry.

2.1 Meso-scale modelling

The unit cell approach is an efficient and robust way to model 3D woven composites. Both elastic properties and damage behaviour can be quite accurately modelled using this approach [6]. In this work, the unit cell models were created using TexGen software [7]. The models are parametrized in terms of number of layers and their orientation, dimension of yarns and spacing between them, and binder path. Some examples of complex textiles are shown in Figure 1. The model parametrisation makes it possible to generate models automatically using a Python script. The models are then meshed using either voxel or octree-based voxel algorithm as shown in Figure 2 [8].

Figure 1: Meso-scale models of 3D reinforcements

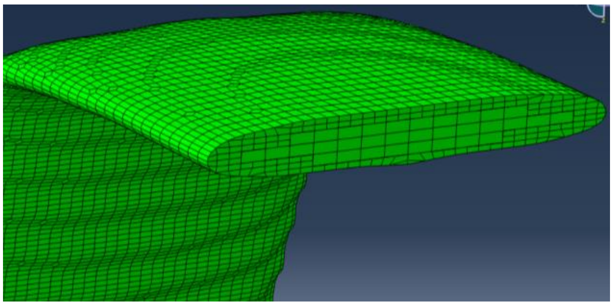

Figure 2: A binder yarn meshed using a smoothed-octree voxel mesh

The unit cell models are then used to predict mechanical properties of composites. It was shown that the elastic properties can be predicted with a good accuracy using a fast orientation averaging approach [6]. More precise methods for the unit cell analysis include full FE analysis using periodic boundary conditions (BCs). Two types of periodic BCs are used in this study: BCs representing continuum material and BCs representing a thin plate. The former BCs are appropriate in cases when the unit cell is smaller than typical dimensions of the macro-scale problem in all dimensions [9] while the latter are suitable for the problems when a thin plate has only one unit cell in the thickness direction [10]. The six loading cases for both types of BCs are shown in Figure 3.

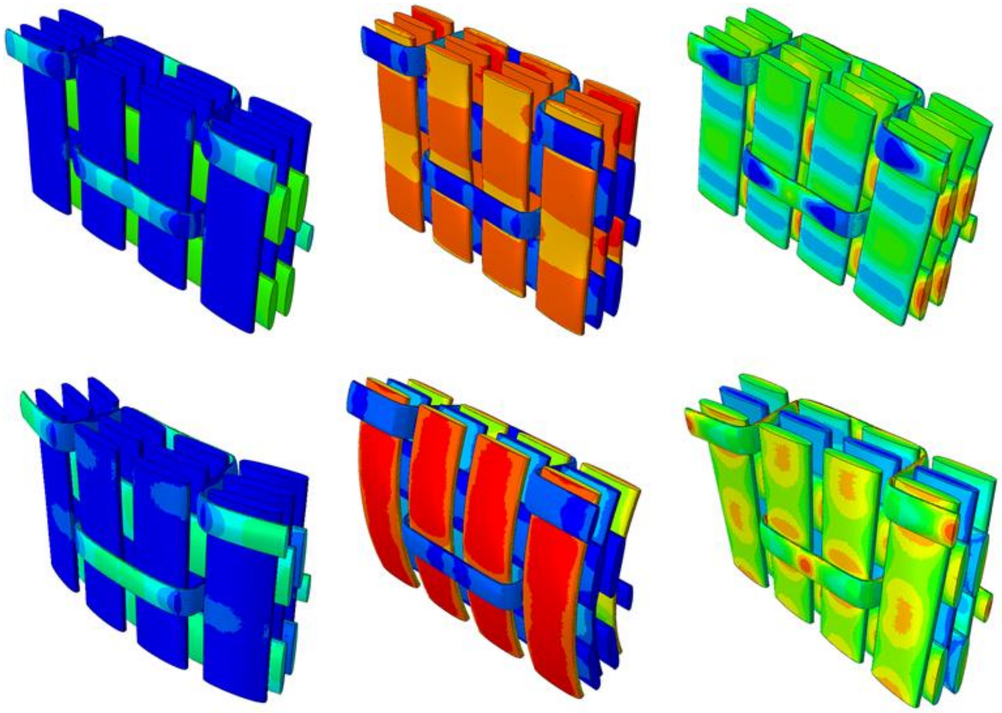

Figure 3: Six loading cases required to determine generalised stiffness matrix of a unit cell

2.2 Optimisation procedure

The goal of an optimisation problem is to minimize an objective function under particular constraints. One of the most common examples of an optimisation problem is minimisation of the weight of a part without significant change of its stiffness/performance. Optimisation of highly non-linear functions is often performed using a genetic algorithm (GA) [2-4].

The present optimisation framework encapsulates a NSGA-II coded in MATLAB [11], the Python scripts for TexGen, scripts to evaluate mechanical properties of a unit cell and a script to evaluate macro-scale response of a composite part. The optimisation algorithm operates with a vector of parameters which are the same as those used to generate unit cell models.

The optimisation algorithm can be used in both single- and multi-objective optimisation problems. The latter results in a set of solutions, which are all optimal and called a Pareto front, as shown in Figure 4. This way of representing optimal solutions provides the end-user an opportunity to identify trade-offs and select an appropriate solution.

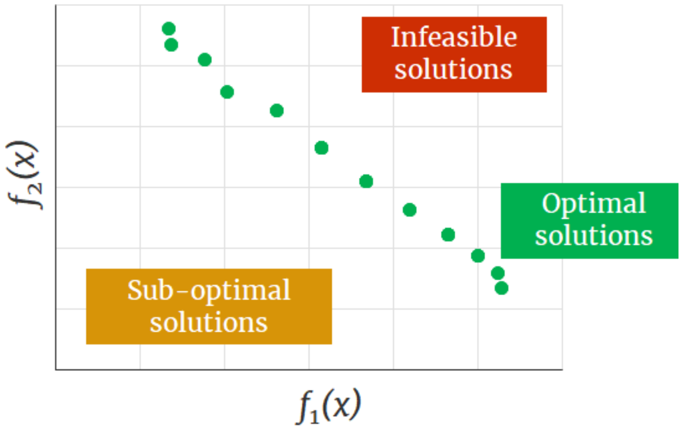

Figure 4: Pareto front of a multi-objective optimisation problem of maximising $f_1(x)$ and $f_2(x)$

3 CASE STUDY

3.1 Automotive floor panel

Geometry of a generic floor panel, which is shown in Figure 5, was provided by AMRC, UK to demonstrate the optimisation framework [12]. As the floor section is to be attached to a vehicle frame, it contributes to its bending and torsional stiffness. Therefore, the two most representative load cases are bending and torsion, which represent the cargo load and tractions from front wheels.

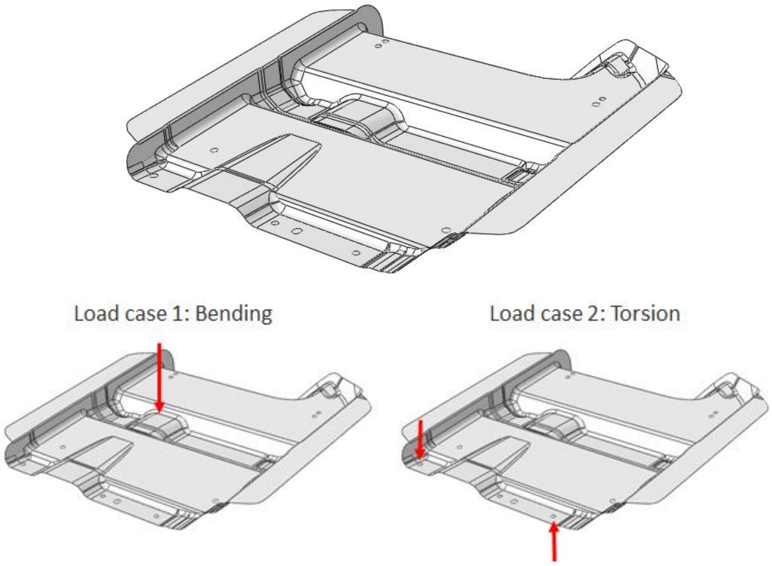

Figure 5: Geometry of a floor section and two loading cases [12]

The floor panel is modelled in Abaqus using shell elements with generalised stiffness matrix. The stiffness matrix is determined using the meso-scale analysis as described in Section 2.1. Bending and torsion properties are evaluated in terms of nodal displacements at point where concentrated forces are applied. In other words, the optimisation problem is to minimise these displacements under constraints of fixed weight or fixed thickness of the part.

Two possible fibre architectures were considered for optimisation: a laminate comprising bi-axial

±45° non-crimp fabrics (NCF) stacked in arbitrary orientations and a multi-axial 3D preform with orthogonal binder. NCFs were modelled as conventional laminates assuming a fibre volume fraction of 60%. Multi-axial preforms had the same fibre volume fraction. Total thickness for all preforms was 2.1 mm which corresponds to the thickness of the panel shown in Figure 5. This thickness corresponds to fibre layers of NCF material and 10 layers of yarns in multi-axial 3D preforms. Properties of T700 carbon fibre were used to calculate yarn properties in the meso-scale models.

Orientation of layers in preforms was enforced to be symmetric but this condition can be relaxed if necessary. Pareto fronts for these optimisation problems are given in Figure 6. As expected, composite designs on the right hand side of these Pareto fronts (best in torsion) tend to include ±30° and ±45° layers, while the design in the left hand side (best in bending) include layers with fibre orientation in 0° and 90°. Designs in between these two extremes include all of these

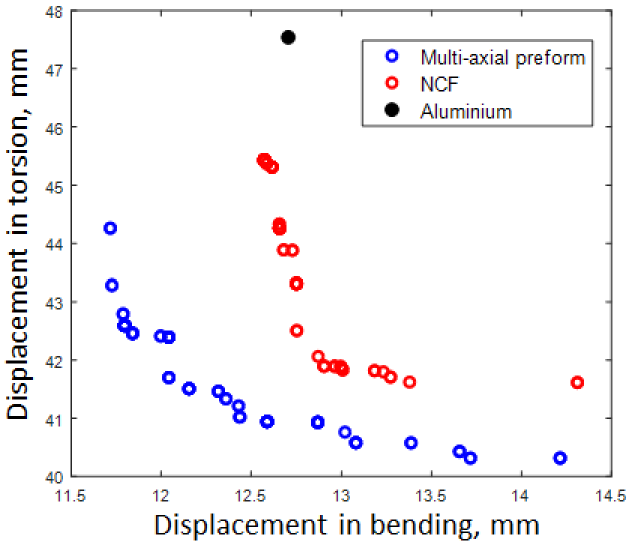

Figure 6: Pareto fronts for two fibre architectures used for the floor section geometry

Numerical analysis showed that replacing aluminium with an optimised NCF layup increases torsional stiffness of the floor panel by about 5% with no change in bending stiffness. It also leads to the weight reduction of 30%. An optimised multi-axial layup can be designed to have both torsional and bending stiffness increased by 10%. This creates a potential to reduce the thickness of the part and reduce the weight even further.

4 MANUFACTURING TECHNOLOGIES FOR NOVEL REINFORCEMENTS

Driven by optimisation an off-axis tow incorporating technique along with combined fibre placement and through-thickness binder yarns with tow steering have been designed to develop the machine (Figure 7). As a result, various types of multiaxial preforms with through-thickness reinforcement can be manufactured through this process.

Figure 7: Off-axis tow placement machine

Using this manufacturing process stuffer tows can be placed in any direction which is not possible on any conventional 3D weaving machine. This process can make thick 3D structures, reduce the wastage and can handle delicate fibres better than commercial weaving process. Two fibre architectures with orientations 90/0/90/0/90 and 90/45/0/-45/90 were produced using the developed technique and are shown in Figure 8.

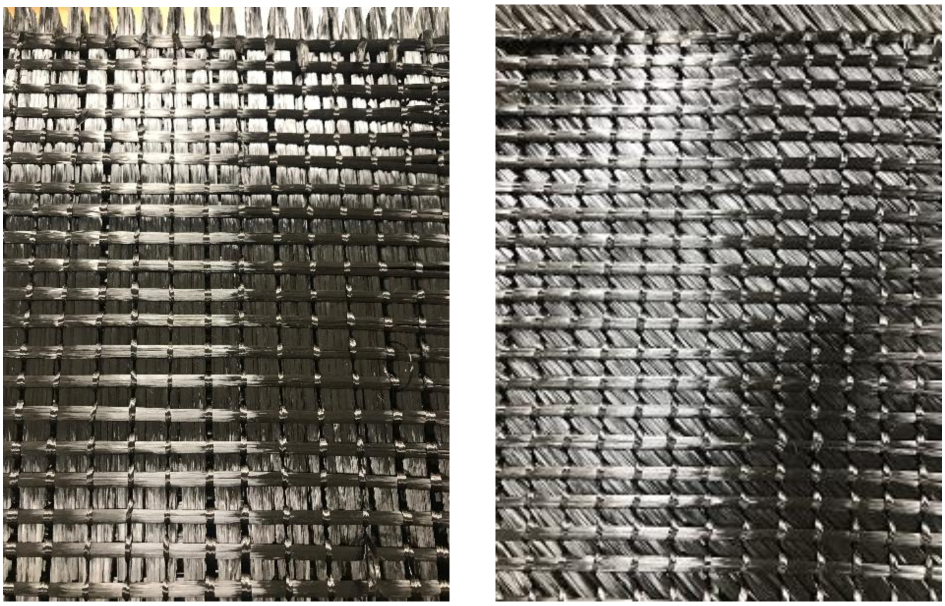

Figure 8: Orthogonal 90/0/90/0/90 (left) and off-axis 90/45/0/-45/90 (right) preforms

Two composite panels produced using resin infusion were used to prepare samples for microscopy [13]. It can be seen in Figure 9 that the warp and weft yarns in the preform with off-axis yarns remained almost straight after the resin infusion. In contrast, the warp yarns in the preform with no off-axis yarns exhibits high crimp. The crimp in the orthogonal preform is a result of relatively loose initial architecture of the preform which can be easily distorted during composite manufacturing. The irregularities in the preforms make it more difficult to model these preform using idealised models as those shown in Figure 1.

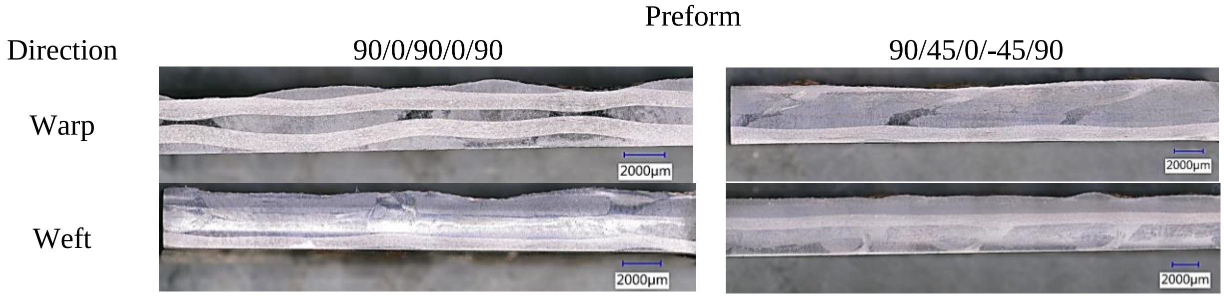

Figure 9: Cross -sectional images of multiaxial composites [13]

5 CONCLUSIONS

The presented framework incorporates existing elements of composites modelling such multi-scale analysis of textile composites and multi-objective optimisation of objective functions with constraints. The framework can be used for meso-scale optimisation of existing fibre architectures e.g. 3D woven composites or tufted laminates as well as for optimisation of preforms which are currently not possible to manufacture. The optimisation framework was demonstrated by optimising a multi-axial 3D preform with orthogonal binder. The optimal solutions for the multi-axial 3D fibre preforms were at least 10% stiffer in bending and torsion and 30% lighter than the same part made from aluminium. It was also shown that such multi-axial 3D preforms have better performance than NCF laminates.

One potential technique to create multi-axial 3D preforms was implemented and will be used to validate the results of the optimisation framework presented here. The validation will include coupon-level validation of the meso-scale models as well as moulding and testing the floor panel geometry.

Further applications of the optimisation framework will include optimisation of pressurised tubular structures. In this case, the objective is not to reduce the weight of these structures but to add damage resistance to it by introducing off-axis reinforcement which is not present in filament-wound structures.

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